Do More Batteries Make A Plug-in Hybrid Better? Implications from Optimal Vehicle Design and Allocation

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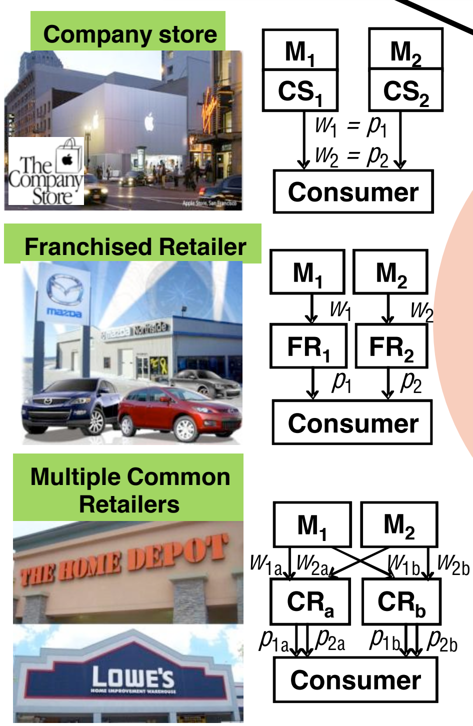
Ching-Shin Norman Shiau
Postdoctoral Research Fellow
Mechanical Engineering
Carnegie Mellon University

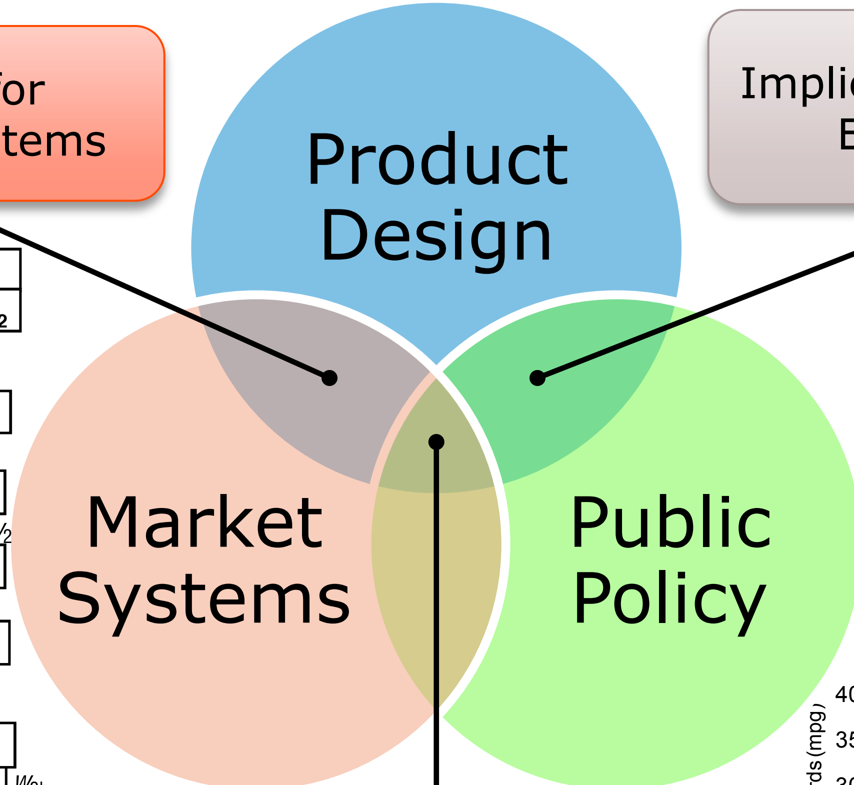
Research Overview

Design for Market Systems

Implications of Vehicle Electrification

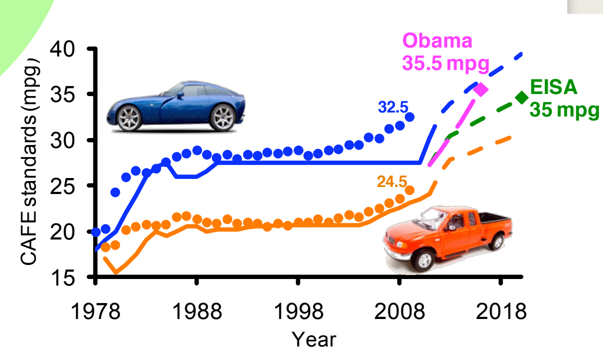


Market Competition and Structure



Plug-in Hybrid

Vehicle Design Decisions for Market and Policy



CAFE Policy

Mechanical Engineering Carnegie Mellon

epp engineering and public policy

Carnegie Mellon Green Design Institute

Carnegie Mellon DESIGN DECISIONS LABORATORY

Plug-in Hybrid Technology

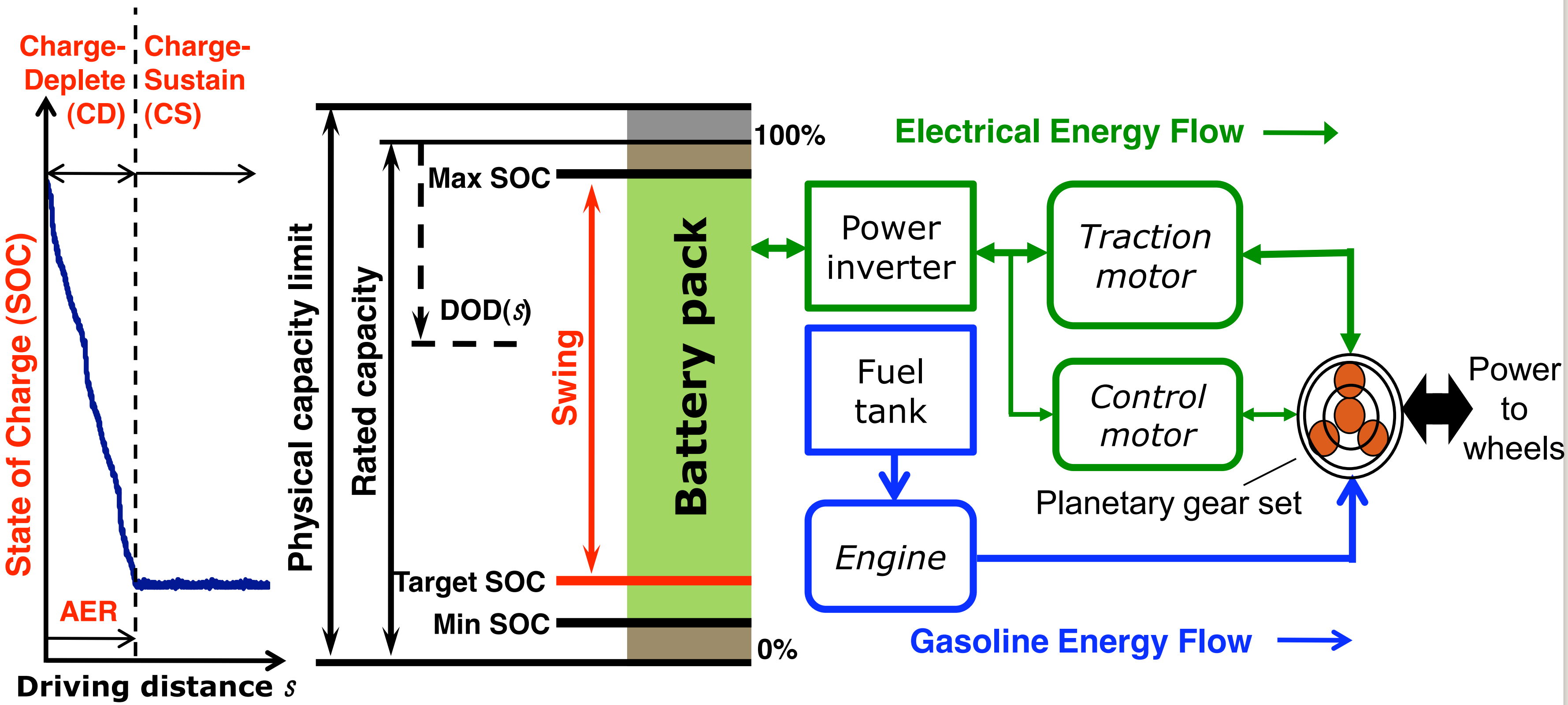
- Public concerns: global warming on GHG emissions and foreign oil dependency in the US transportation sector
- Plug-in hybrid electric vehicle (PHEV) is considered as a potential technology to address these issues
- Net effects of PHEVs depend critically on vehicle design and battery technology

What are the economic and environmental implications of plug-in hybrid vehicles?

Vehicle Technologies

	 CV	 HEV	 PHEV	 BEV
Power Convertor	Engine	Engine & Motor	Engine & Motor	Motor
Battery Pack	None	Small	Medium	Large
Gasoline 	X	X	X	
Electricity 			X	X

PHEV Powertrain System

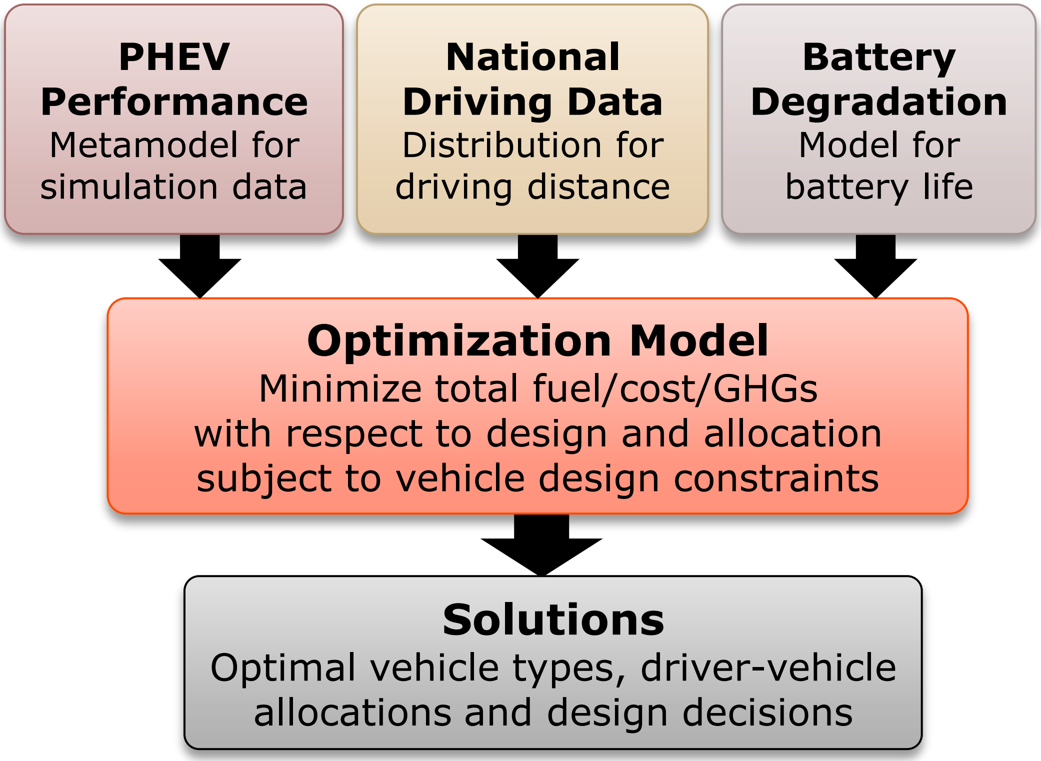


PHEV Literature Review

- Prior PHEV Studies
  - EPRI Report (2001)
  - Simpson [NREL] (2006)
  - EPRI-NRDC Report (2007)
  - Lemoine, Kammen, and Farrell [UC Berkeley] (2008)
  - Samaras and Meisterling [CMU-EPP] (2008)
  - Kromer and Heywood [MIT] (2009)
  - Sioshansi and Denholm [NREL] (2009)
  - NRC PHEV analysis report (2009)
  - Plotkin and Singh [ANL] (2009)
- This study focuses on the implications of optimal PHEV designs and driver allocations on life cycle performance

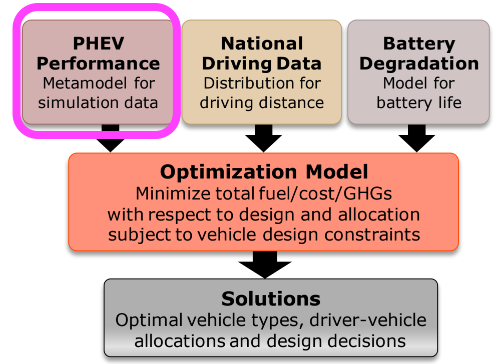
What are the best vehicle choices to reducing life cycle GHGs, cost and fuel consumption?

PHEV Optimization Framework

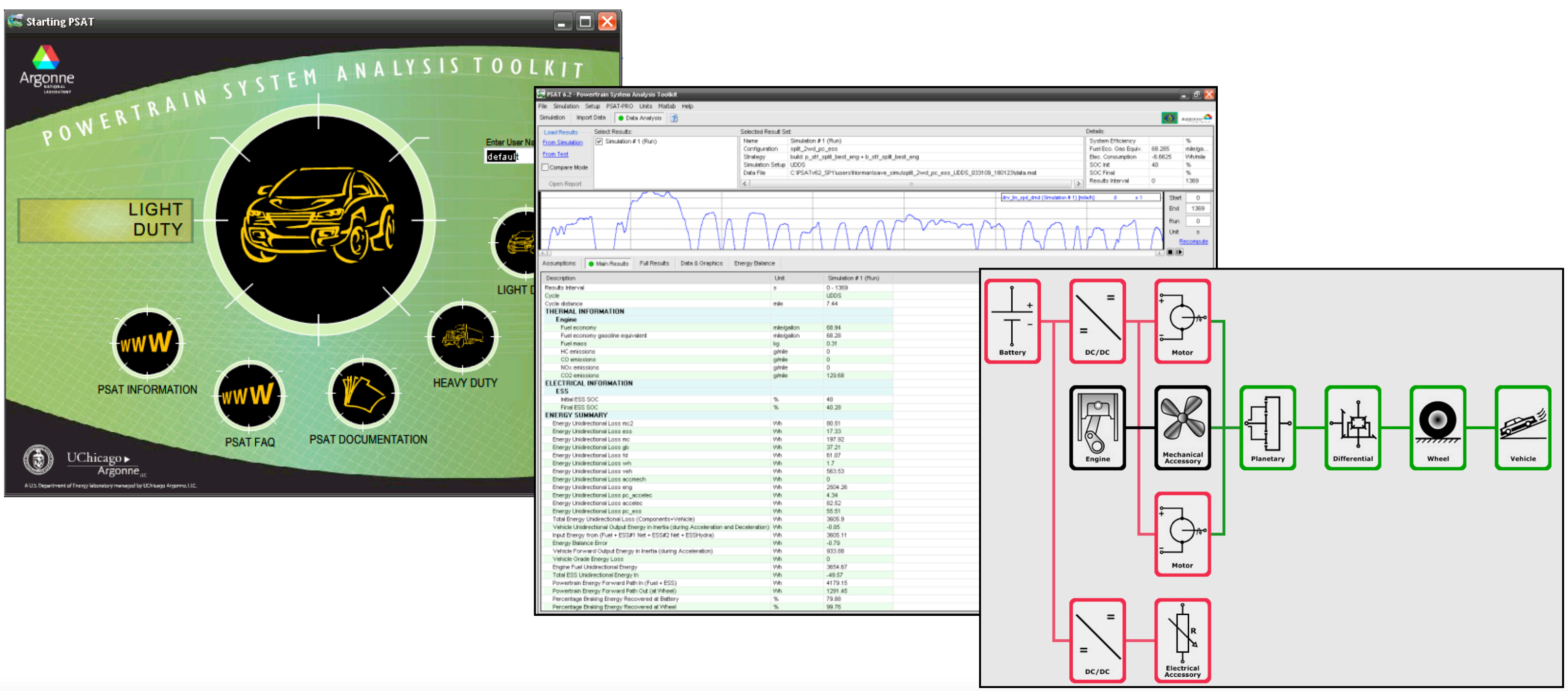


Benevolent dictator to determine optimal PHEV designs and driver allocations for social objectives

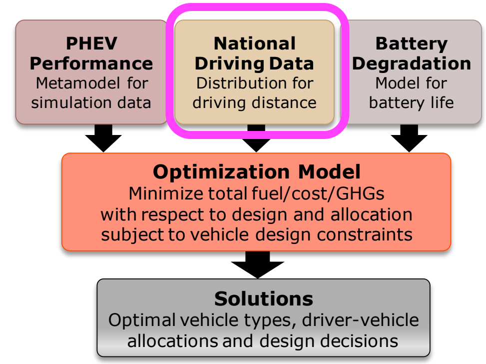
Vehicle Simulation



- Use the Powertrain Systems Analysis Toolkit (PSAT) vehicle simulator developed by Argonne National Laboratory (ANL)
- Start with a model of a Toyota Prius
- Use EPA UDDS cycles to test PHEV performance

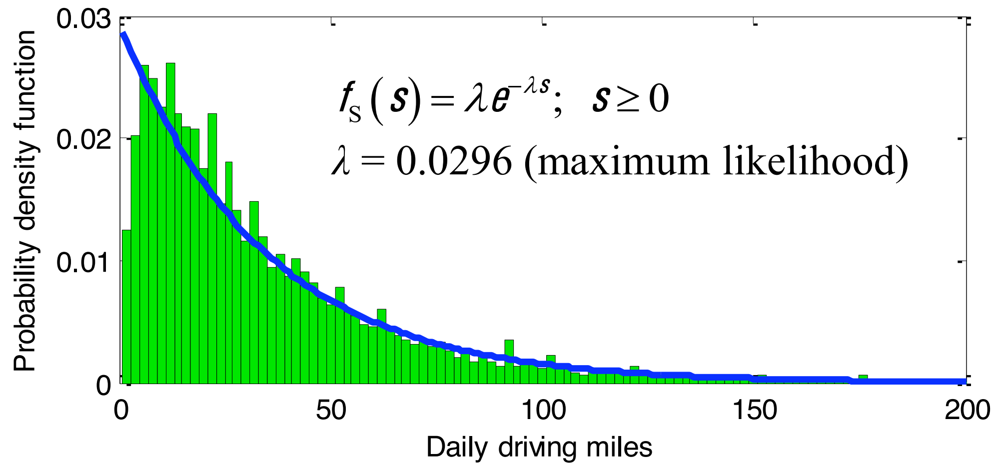


Daily travel distribution



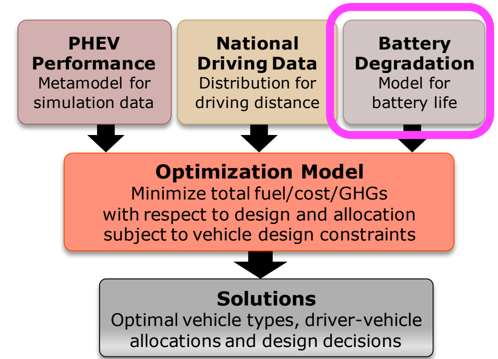
NHTS National Household Travel Survey
Our Nation's Travel

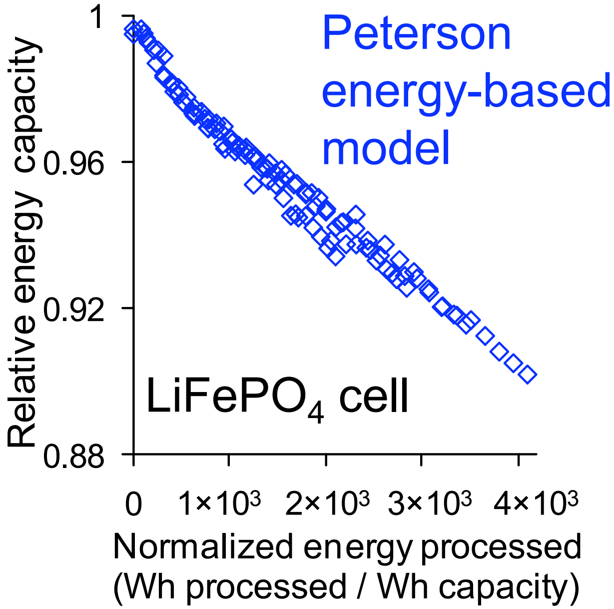
- Use the 2009 NHTS data to estimate the national average distance driven per day over the population of drivers
- Size of the 2009 survey: 136,410 households
- We fit the weighted driving data using the exponential distribution

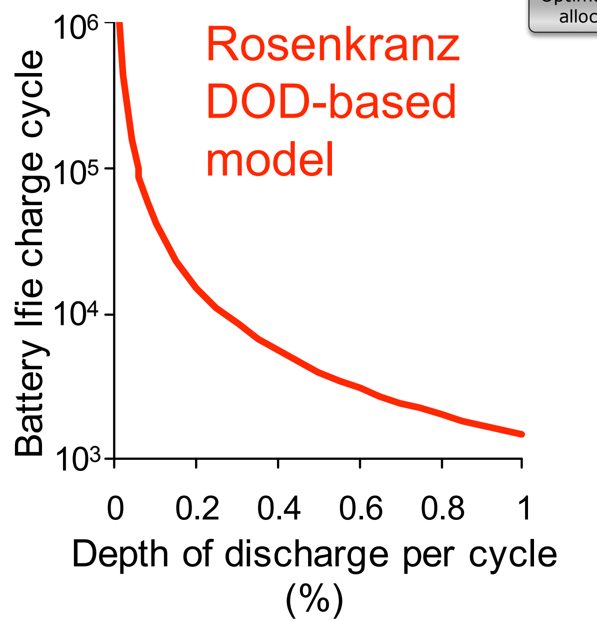


Federal Highway Administration, 2010, "National Household Travel Survey 2009," Department of Transportation, Washington, DC.

Battery degradation





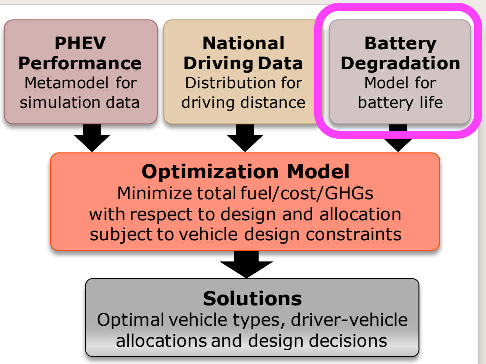


Markel and Simpson [NREL] (2006)
Simpson [NREL] (2006)
Kromer and Heywood [MIT] (2009)

Peterson, S.B., Whitacre, J.F., and Apt, J. (2010) Lithium-Ion Battery Cell Degradation Resulting from Realistic Vehicle and Vehicle-to-Grid Utilization. Journal of Power Sources. 195(8) 2385–2392.

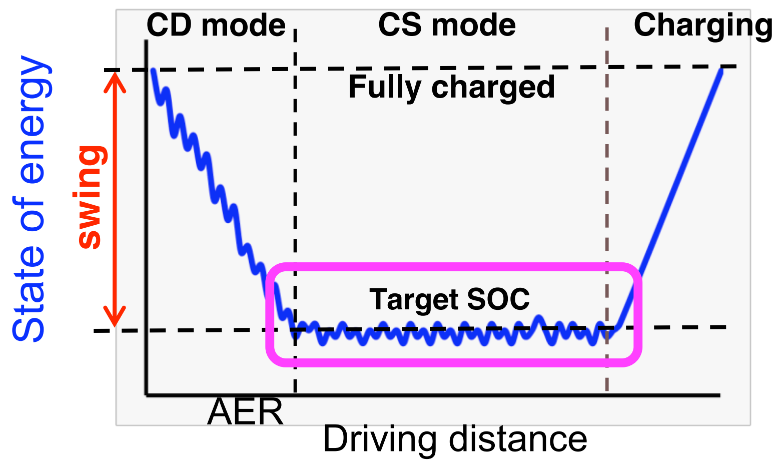
Rosenkranz, K. (2003) Deep-Cycle Batteries for Plug-in Hybrid Application. Presentation in EVS-20 Plug-In Hybrid Vehicle Workshop, November 16-19, Long Beach, CA

Estimated battery life using two models

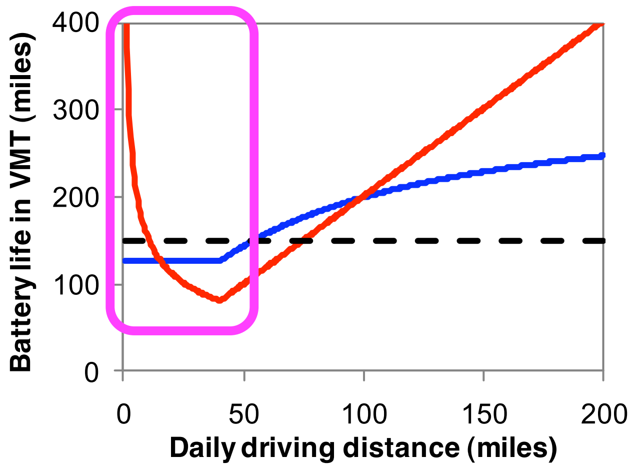


- Rosenkranz model
  - Not account for the battery degradation in CS mode because of no DOD variation
  - Can be too optimistic for short distance driving
- Peterson model
  - Tested under variable C-rate
  - Account for energy processed in CS mode and charging

Battery energy status

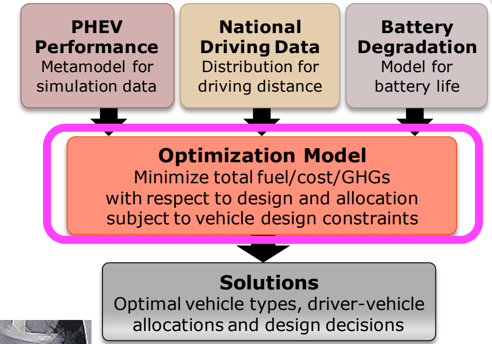


Battery life in VMT



Plots using a PHEV40 with battery 9.5kWh and swing at 80%

Objective Functions



Design variables:

$\mathbf{x}$ = vehicle design variable (engine, motor, battery and swing)

s_i = vehicle allocation range

Fuel consumption per day:

$$f_{\mathrm{G}}(\mathrm{x}, s) = \frac{s_{\mathrm{G}}}{\eta_{\mathrm{G}}}$$

η = efficiency (miles/kWh or miles/gal)

Average lifecycle GHG emissions per day:

$$f_{\mathrm{V}}(\mathrm{x}, s) = \underbrace{v_{\mathrm{OP}}}_{\text{operating}} + \underbrace{\frac{v_{\mathrm{VEH}}}{TD}}_{\text{vehicle}} + \underbrace{\begin{cases} \text{Buy:} & v_{\mathrm{BAT}}/T \\ \text{Lease:} & v_{\mathrm{BAT}}/B \end{cases}}_{\text{battery}}$$

T: vehicle life year

B: battery life year

D: driving days per year

Equivalent annualized cost (EAC) per day:

$$f_{\mathrm{C}}(\mathrm{x}, s) = \underbrace{c_{\mathrm{OP}} \frac{CRF(r_{\mathrm{N}}, T)}{CRF(r_{\mathrm{R}}, T)}}_{\text{operating}} + \underbrace{\frac{c_{\mathrm{VEH}} \cdot CRF(r_{\mathrm{N}}, T)}{D}}_{\text{vehicle}} + \underbrace{\frac{1}{D}\begin{cases} \text{Buy:} & c_{\mathrm{BAT}} \cdot CRF(r_{\mathrm{N}}, T) \\ \text{Lease:} & c_{\mathrm{BAT}} \cdot CRF(r_{\mathrm{N}}, B) \end{cases}}_{\text{battery}}$$

r_{N}: nominal (market) discount rate

r_{R}: real (inflation-free) discount rate

Constraints:

0-60mph acceleration time, minimum SOC after multiple US06 cycles

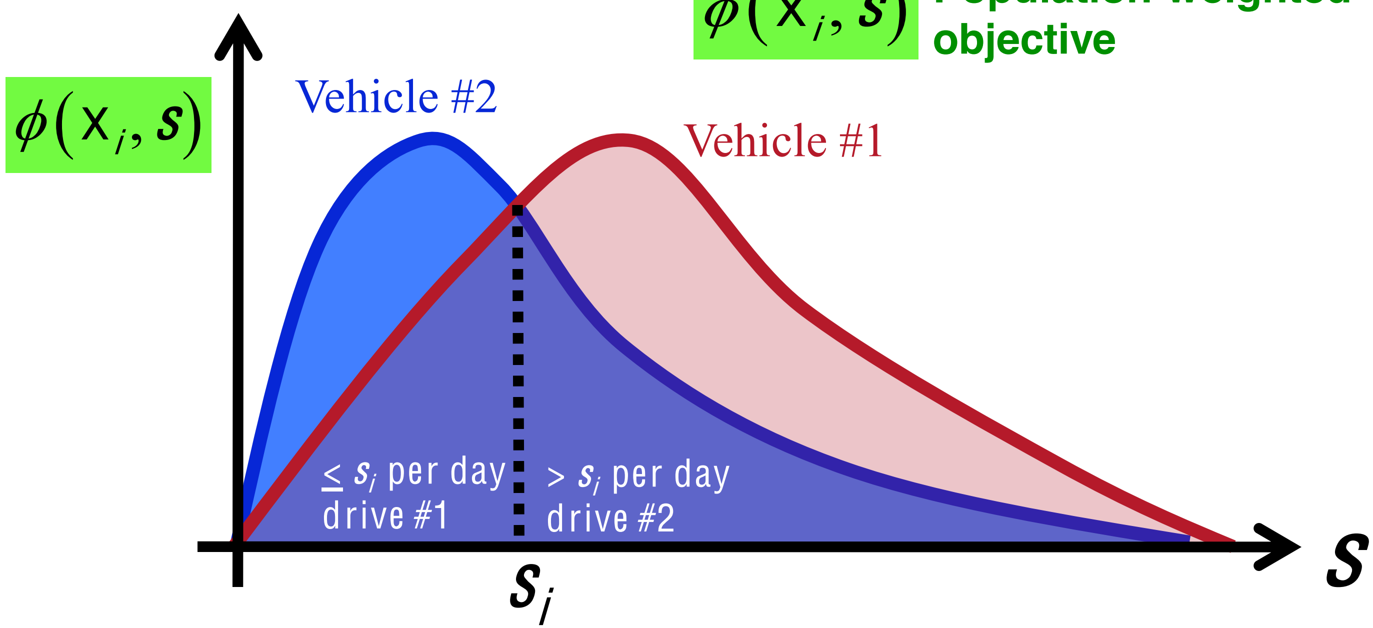
Core concept of the optimization model

Objective function per day {\$, GHG, gal}

pdf of distance driven per day

$$\underset{x_i, s_i \ \forall i \in \{1,\ldots,n\}}{\text{minimize}} \sum_{i=1}^{n} \left(\int_{s_{i-1}}^{s_i} \underbrace{f_O(x_i, s)\ f_S(s)}_{\phi(x_i, s)} ds \right)$$

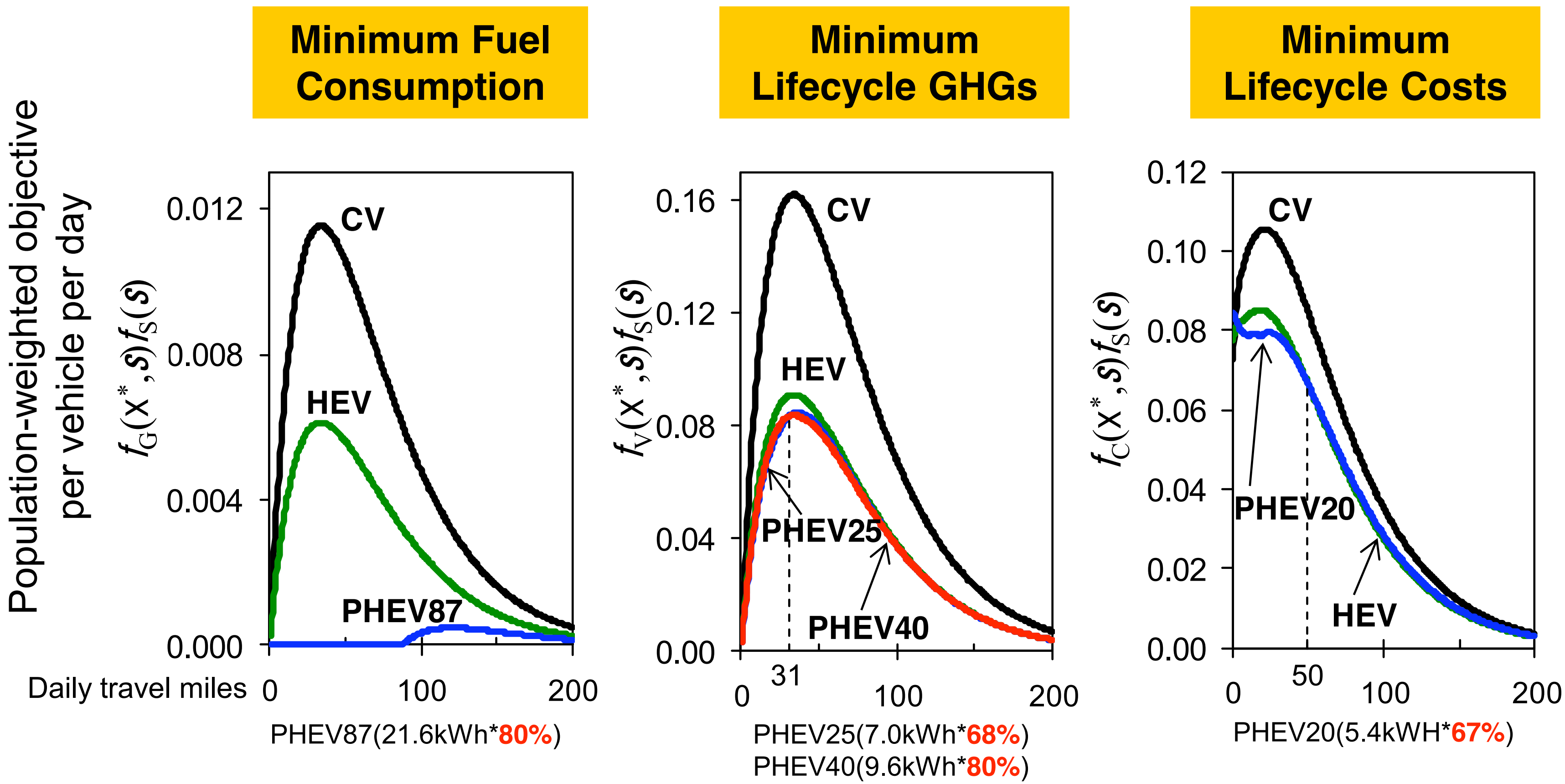
Population-weighted objective



Assumptions

- Fuel and electric efficiency estimated by UDDS cycles
- $400 per kWh Li-ion battery pack cost (PHEV)
- $600 per kWh NiMH battery pack cost (HEV)
- $3.30 per gal gasoline (2008 average)
- $0.11 per kWh electricity (2008 average)
- 0.69 kg-CO_2-eq/kWh grid emission (US average mix)
- $0 per ton-$CO_2$-eq allowance price
- 5% discount rate
- EPRI powertrain cost model
- Buy-lease battery replacement
- Peterson battery degradation model

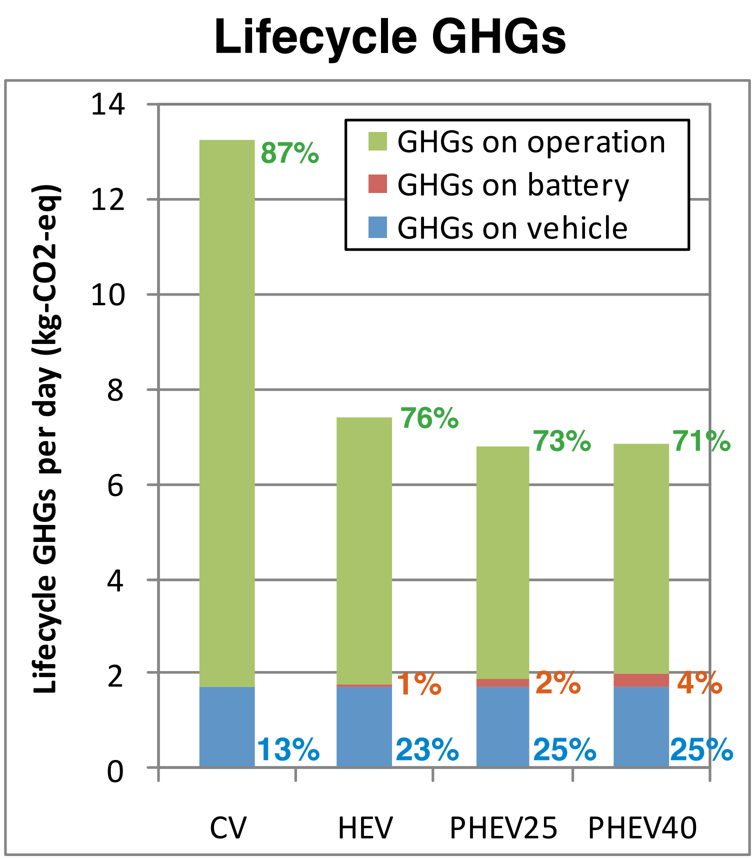
Optimal PHEV Designs and Allocations

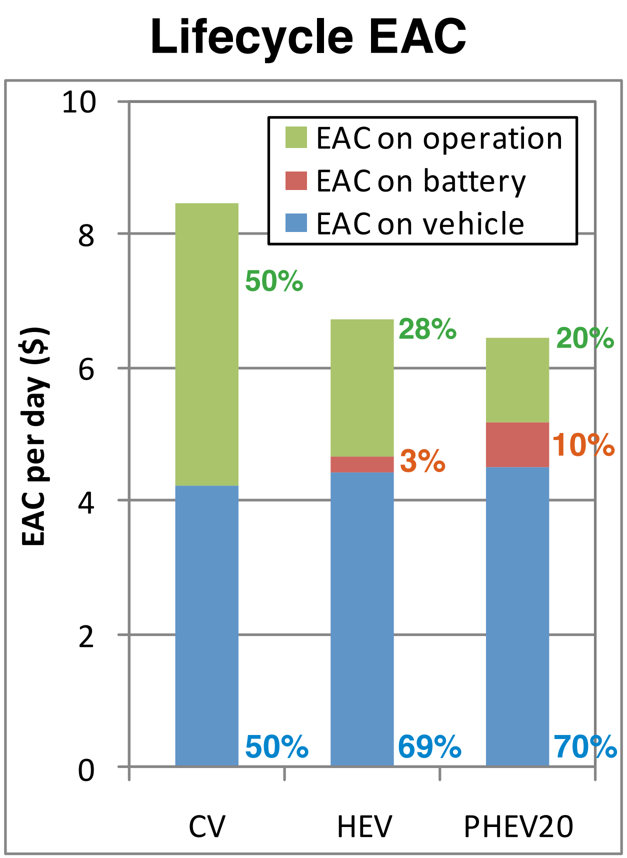


Base case settings:
Buy-lease battery replacement, Peterson battery degradation model, \$400/kWh Li-ion battery cost, \$600/kWh NiMH cost, \$3.30/gal gasoline, \$0.11/kWh electricity, grid emission 0.69 kg-CO_2-eq/kWh, \$0/ton CO_2-eq allowance price, and 5% discount rate

Breakdown analysis

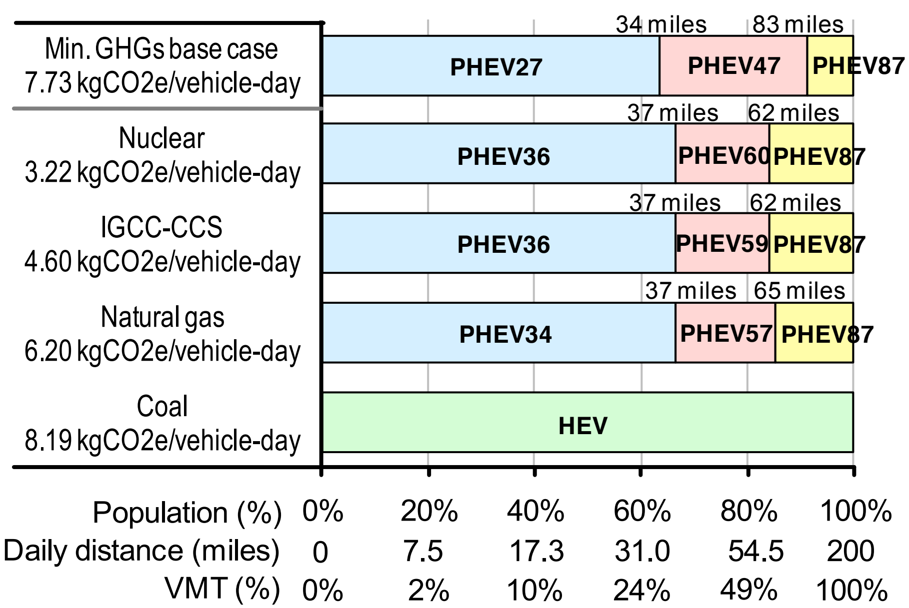
Assume travel distance 30 miles a day





Sensitivity analysis for min. GHGs

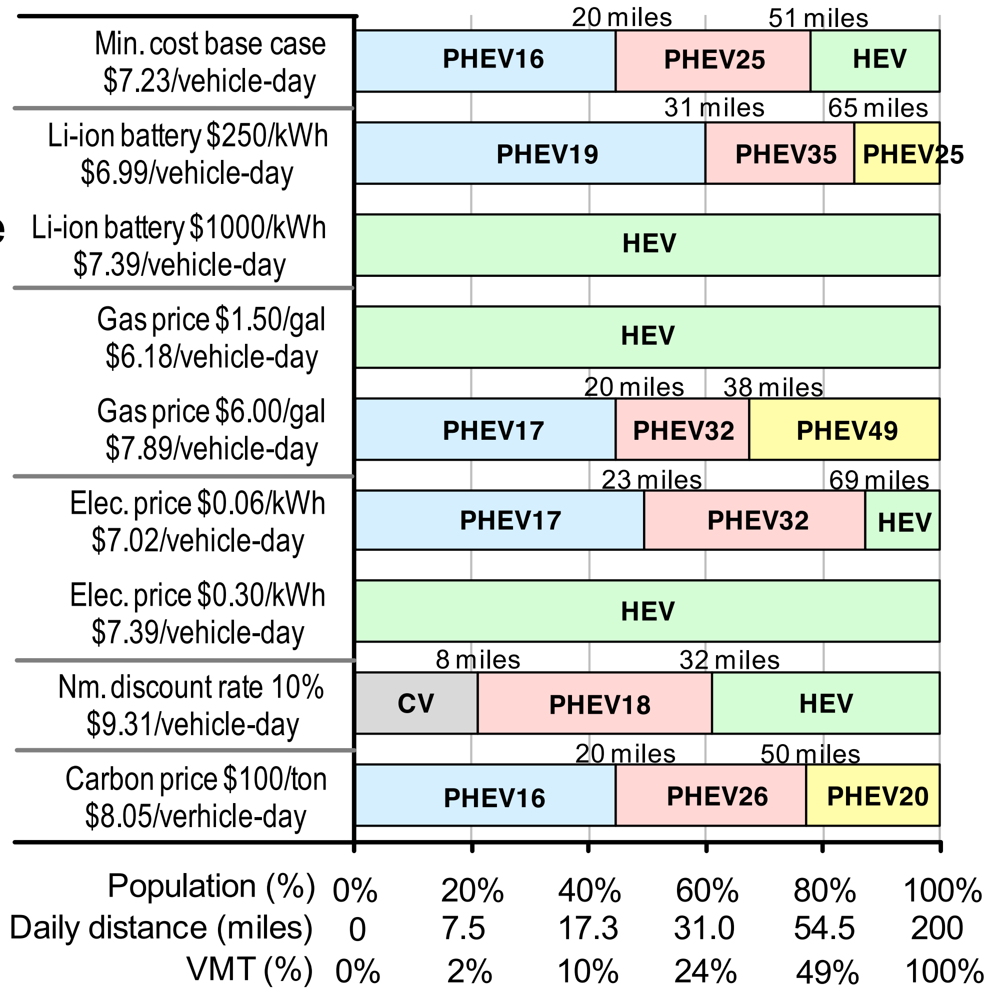
• US average grid mix:	0.69 kg-CO_2e/kWh	(Weber et al., 2010)
• Nuclear:	0.07 kg-CO_2e/kWh	(Sovacool, 2008)
• IGCC w/ CCS:	0.25 kg-CO_2e/kWh	(Jaramillo et al., 2009)
• Natural gas:	0.47 kg-CO_2e/kWh	(Weisser, 2007)
• Coal:	0.90 kg-CO_2e/kWh	(Weisser, 2007)



Sensitivity analysis for min. cost

- Consider 3-vehicle segment as base case
- High battery cost, low gas price and high elec. price make PHEV not cost competitive
- To make PHEVs part of the least-cost solution:

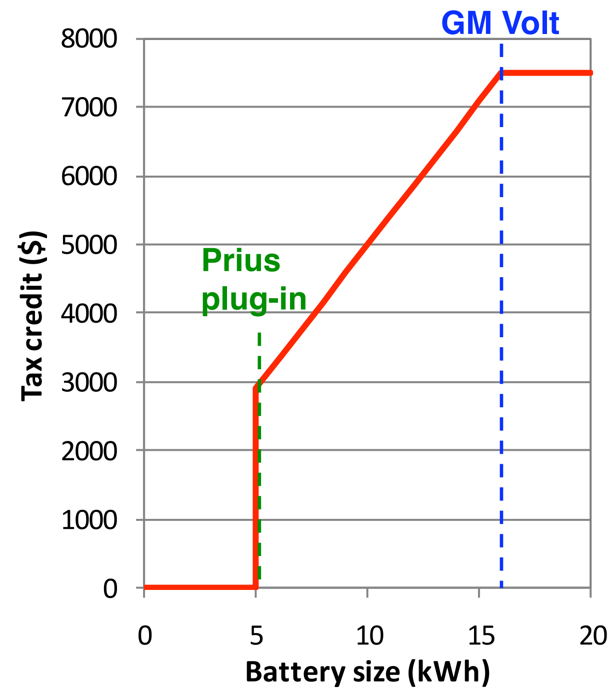
  Li-ion < $590/kWh at 5%
  Li-ion < $410/kWh at 10%



ARRA tax credit vs. carbon tax

- Tax credit in the American Recovery and Reinvestment Act (ARRA) for battery size in PHEV/EV

Tax credit in the ARRA bill (Page 212-219)
Light-duty vehicles: Vehicle base amount is \$2,500 for a PHEV can draw propulsion energy from a battery with not less than 5 kWh of capacity (base \$417), plus \$417 for each kWh of capacity in excess of 5 kilowatt hours. Total amount for battery shall not exceed \$5,000. Thus the tax credit can be calculated by $\min(\$7500, \$2500 + \$417 + \$417*(kWh - 5))$



- ARRA incentivizes PHEVs with larger batteries (AER 33-49), which results in 6% higher social costs than under a \$100/ton CO_2 tax scenario

ARRA: http://fdsys.gpo.gov/fdsys/pkg/BILLS-111hr1ENR/pdf/BILLS-111hr1ENR.pdf

More sensitivity tests

- Alternative vehicle base costs and powertrain cost models
  - ➔ The base case optimal solution is robust
- Battery life must outlast vehicle life
  - ➔ Optimal battery swing reduced 2-5%
- Battery leasing (prorated: paid per portion)
  - ➔ Larger battery packs with reduced swings
- Battery end of life (EOL) at 20% capacity fade
  - ➔ Makes PHEVs less cost competitive
- Rosenkranz DOD-base degradation model
  - ➔ Optimal PHEV11 with a 5.2 kWh battery at 39% swing (a battery size equivalent to a PHEV23 at 80% swing)

Take away 1

- Large PHEVs with AER > 50 miles can reduce petroleum consumption
- PHEVs with AER 25-50 miles can reduce GHGs
- PHEVs with AER 15-25 miles for short distance travel and HEVs for longer distance travel can save cost
- Li-ion battery pack cost below $590/kWh at a 5% discount rate (or below $410/kWh at 10%) to make PHEV part of least-cost choice

Take away 2

- Battery swing in excess of 60% with $LiFePO_4$ technology should be utilized to achieve minimum life cycle cost, GHGs, and petroleum consumption
- Carbon allowance prices have marginal impact on optimal design or allocation of PHEVs
- Battery tax credit in the ARRA bill may result in higher net costs than under a \$100/ton CO_2 tax scenario

Future work

- Consumer and market behaviors
- PHEV performance on real-world driving cycles
- Uncertainty in GHG emissions
  - Regional effects, charge timing, and marginal dispatch
- Battery technology
  - Thin-electrode for high-power and thick-electrode for high-energy batteries
  - Calendar (storage) degradation
  - Blended-mode PHEVs
- Gasoline prices and grid characteristics can become endogenous after significant PHEV market penetration

Publications

Shiau, C.-S.N. and J.J. Michalek (2009) Optimal product design under price competition. ASME Journal of Mechanical Design, 131(7), 071003.

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Shiau, C.-S.N., J.J. Michalek and C.T. Hendrickson (2009) A structural analysis of vehicle design responses to Corporate Average Fuel Economy policy. Transportation Research Part A: Policy and Practice, 43(9-10), 814-828.

Shiau, C.-S.N., J.J. Michalek, N. Kaushal, C.T. Hendrickson, S.B. Peterson and J.F. Whitacre (2010) Optimal plug-in hybrid electric vehicle design and allocation for minimum life cycle cost, petroleum consumption and greenhouse gas emissions. ASME Journal of Mechanical Design: Special Issue on Sustainable Design, In review.

And 9 peer-reviewed conference papers.

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